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(6) HEATING OF THE ELECTRONS
IN THE F REGION OF THE IONOSPHERE, (7)NA (8)U (9)NA

(10) by

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(5) 829 660

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ABSTRACT

↓ An experiment to cause artificial changes in the electron-density profile of the F region of the ionosphere was conducted in order to experimentally verify the theoretical conclusion, ~~described in detail by D. T. Farley [Ref. 1]~~, that the electrons in the F region could be artificially heated by a radio wave. An antenna array, fed by a 40 kw transmitter, was used to illuminate a portion of the ionosphere at a frequency slightly below the critical frequency. An absorption of energy from this beam by the electrons in this layer was expected, thereby increasing the average electron temperature and modifying the density profile. With the equipment used for this experiment, a $3\frac{1}{2}$ -percent decrease in the maximum of the electron-density profile, corresponding to a reduction of 135 kc in the observed critical frequency 7700 kc, was expected. A phase-path sounder used to measure changes in the phase-path height, and vertical-incidence sounder used to measure the virtual height, (both estimated to be sensitive to a 50-kc change in the critical frequency) were unable to detect any changes in several trials of the experiment. ↑

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I. INTRODUCTION

Heating the ionosphere with radio waves, especially at frequencies near the gyro-frequency, is not a new concept and much has been written on the subject. But heating the ionosphere at frequencies near the critical frequency has as yet been untried. Theoretical work has been done however, and Farley [Ref. 1], who has presented a detailed discussion of the subject, derived steady-state expressions for the electron-density and temperature profiles as a function of the transmitter parameters. In an attempt to verify these expressions, a radio beam was directed toward the ionosphere from a large antenna array located on the Stanford campus. By inserting the values of the parameters involved in this experiment into the expressions derived by Farley, expected magnitudes of changes were calculated. A sounder, sensitive to changes in the vertical-phase path height, and a vertical-incidence sounder were used to record any artificial changes resulting from changes in the electron-density profile.

II. ANTENNA ARRAY AND TRANSMITTER

The antenna array consisted of 21 center-fed dipoles. Each dipole was cut to a length equal to 0.64 wavelength or 25 meters. The array was formed by three columns of seven parallel dipoles in each column. In constructing the array, compensation was made for variations in the existing terrain level so that the plane of the antenna was as close to 0-deg elevation as possible (i.e., the beam of the array pointed to the zenith). The physical layout of the heating antenna and the associated measuring equipment is shown in Fig. 1. In an attempt to increase the efficiency of the antenna, a single, copper, ground wire was fixed 18 ft below each dipole, parallel to it, to act as a reflector.

The seven dipoles in each column were fed in parallel, each connected by a full-wavelength transmission line. Each of the three columns was then connected to a quarter-wave matching section and these were then all connected in parallel to a 600-ohm, open-wire transmission line. The array was matched to the transmitter by adjusting the impedance of the three quarter-wave matching sections in each column. Figure 2 is a diagram of the array.

The input impedance of the array measured at the transmitter was 200 ohms, making the standing-wave ratio on the main transmission line 3:1. The total loss in the 600-ohm, open-wire transmission line between the transmitter and antenna (approximately 530 meters) at 7700 kc, including the effects of this standing-wave ratio, was calculated to be of the order of 0.1 db. The measured beamwidth was found to be 12 deg and nearly symmetrical about an axis perpendicular through the center of the array.

The transmitter used to excite the array was a military type FRT 22. The dc input to the final stage was 10 amp at 6 kv, giving approximately 40 kw at a 70-percent efficiency. The frequency was constant at 7700 kc.

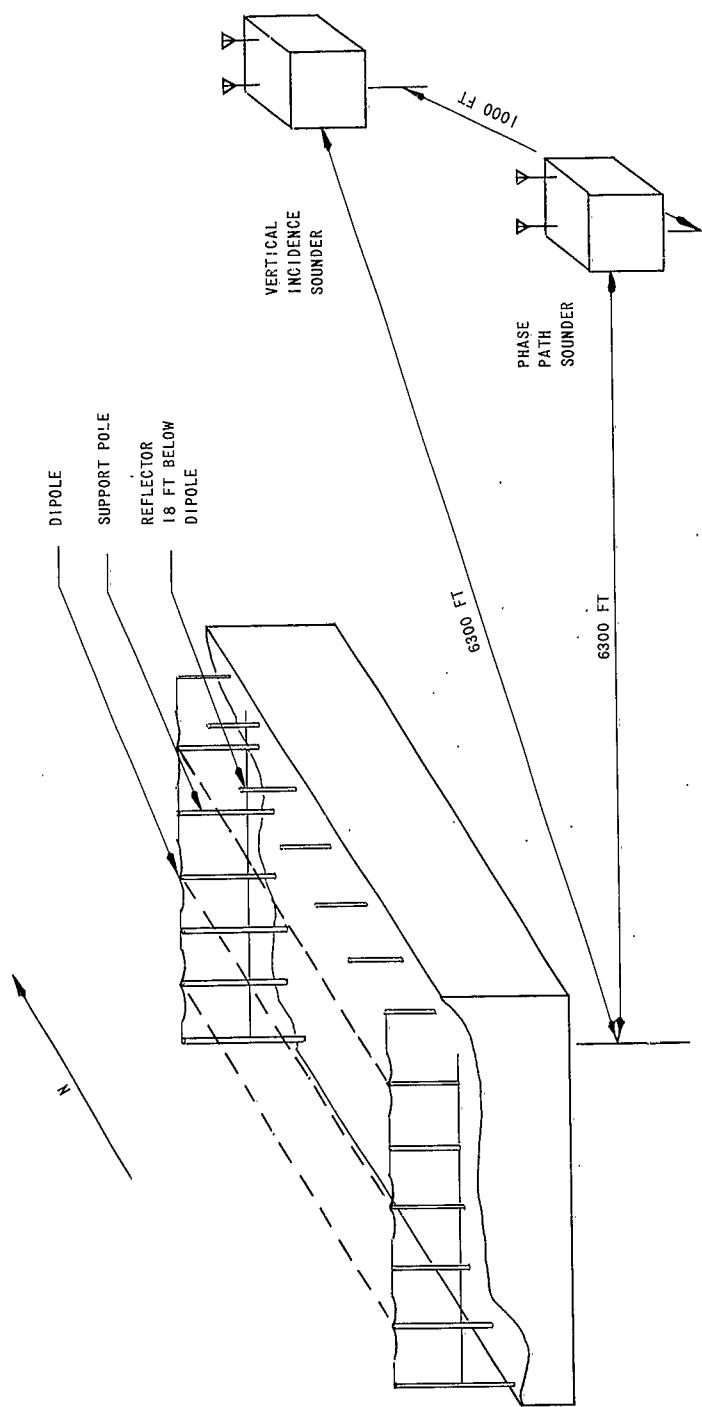


FIG. 1. PHYSICAL ORIENTATION OF ANTENNA ARRAY USED TO ARTIFICIALLY HEAT THE ELECTRONS IN THE F REGION OF THE IONOSPHERE:

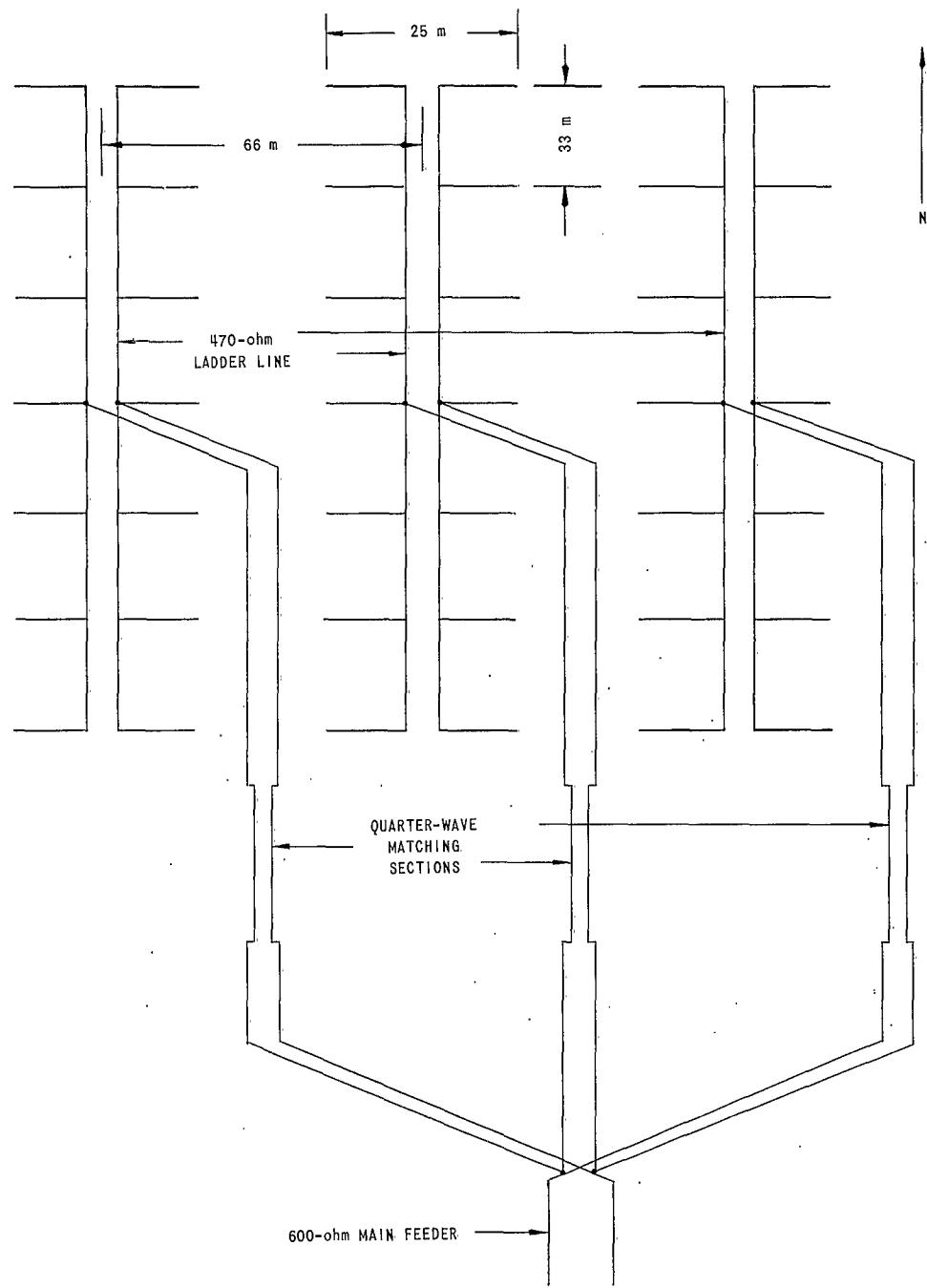


FIG. 2. ANTENNA ARRAY USED TO ARTIFICIALLY HEAT THE ELECTRONS IN THE F REGION OF THE IONOSPHERE.

III. EXPERIMENTAL PROCEDURE

Extraction of energy from the "heating" radio wave by the electrons in the F region of the ionosphere was expected, thereby increasing the average electron temperature with respect to the heavier particles. This temperature increase would result in a decrease in electron density and a decrease in the critical frequency of the F region. Since the frequency of the transmitter could not be changed easily, the experiment was performed during the time of day when the critical frequencies were near the transmitter frequency, 7700 kc. The time for the electron temperature to make a change from equilibrium was expected to be of the order of 10 sec; therefore, the transmitter was pulsed on and off in 30-sec intervals to allow sufficient time to observe any changes.

A vertical-incidence sounder was operated every 15 min to record the critical frequencies of the F region as a function of time. In all but one trial of the experiment, information supplied by the vertical-incidence sounder was used only to determine when the heating equipment should be turned on, so that the experiment could be performed when the critical frequencies were near 7700 kc. Any artificial changes in the ionosphere were expected to appear on the film record made by the phase-path sounder. The experiment was performed on 11, 12, 16, 17, and 23 October and 6 November 1962.

During the 23 October 1962 experiment, the vertical-incidence sounder was operated "manually" by holding constant its frequency at 7600 kc (100 kc below the heating frequency) instead of allowing it to sweep and make a continuous record. When the equipment was operated this way, echoes from both the X and O rays were observed and a change in virtual height corresponding to a change of 50 kc in the critical frequency could have been detected. In this one trial no changes could be observed.

IV. PHASE-PATH SOUNDER

Equipment similar to the type described by J. W. Findlay [Ref. 2] was used to detect changes in the round-trip phase path to the ionosphere. Figure 3 is a block diagram of this phase-path sounder. A transmitter, tuned to a frequency 50 kc lower than the heating frequency (7700 kc), was gated by 200- μ sec-wide pulses at a 50-pps rate. The output of the receiver, which receives both the transmitted and the reflected pulses, is displayed on an oscilloscope. These received signals are beat with a signal from a local oscillator in the detector stage of the receiver to provide an output of a short sinusoidal trace on the oscilloscope. This local oscillator is adjusted to provide two complete sinusoidal cycles within the 200- μ sec keying interval. The first peak of the transmitted pulse is used to trigger the oscilloscope sweep, thereby locking the displayed phase position of the transmitted pulse.

The reflected signal from the ionosphere will be of the form $e_r = E_r \sin \omega_0 (t - P/c)$, where ω_0 is the angular frequency of the transmitted signal and P is the round-trip phase path given by

$$P = c \int_{\text{path}} \frac{ds}{v_p},$$

where v_p is the phase velocity over the interval (ds) of path length, and c = velocity of light. The receiver output will be of the form (within the 200- μ sec keying interval):

$$e_0 = E_0 \sin \left(2\pi f_2 t - \frac{\omega_0 P}{c} \right),$$

where f_2 is 10 kc. For the displayed signal to shift an amount equal to the distance between successive peaks, $\omega_0 P/c$ must change by 2π . Therefore $(\omega_0/c) \Delta P = 2\pi$ and $\Delta P = 2\pi c/\omega_0 = \lambda_0$. A change of one free-space wavelength (of the transmitted signal) in the phase path will cause the displayed signal to shift an amount equal to the distance between successive peaks.

The output of the receiver was used to intensity modulate the beam of an oscilloscope, while a film was slowly passed over the display. A portion of the film record taken on 16 November 1962 is shown in Fig. 4. The lower traces in these records are the peaks of the transmitted signal, locked in phase by triggering the oscilloscope sweep with the first peak. The upper traces are the peaks of the reflected signal. The uniform shift in phase of these traces is due to the natural changes in the phase path. Figure 5 is the phase-path record for the same day, with the horizontal gain of the oscilloscope increased and the trace repositioned to eliminate the traces of the transmitted pulses.

The sensitivity, limited by the physical parameters of the equipment, was estimated to be +50 kc in terms of changes in the critical frequency.

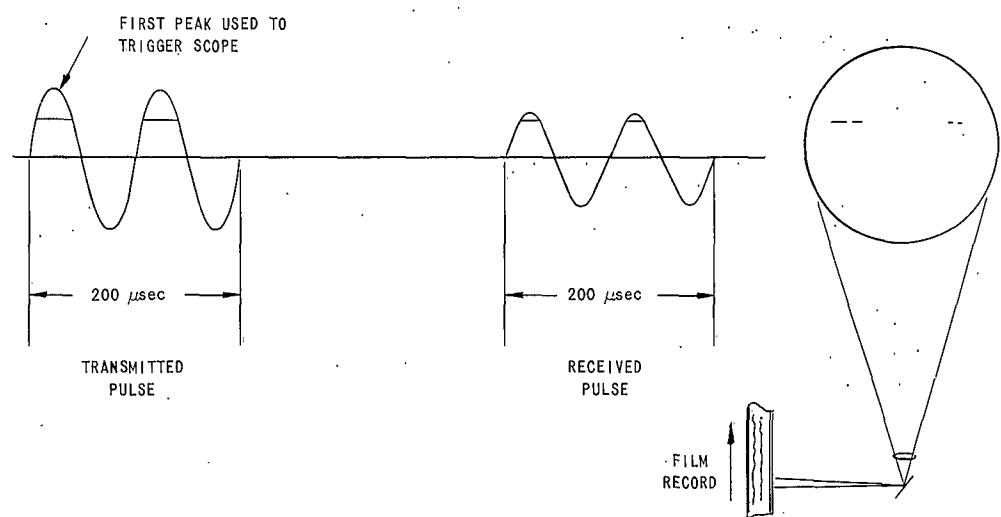
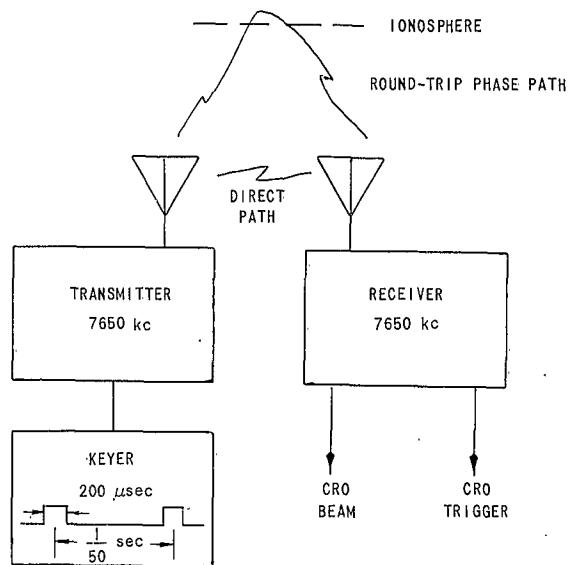


FIG. 3. BLOCK DIAGRAM OF THE PHASE-PATH SOUNDER
AND TYPICAL RESULTING TRACE.

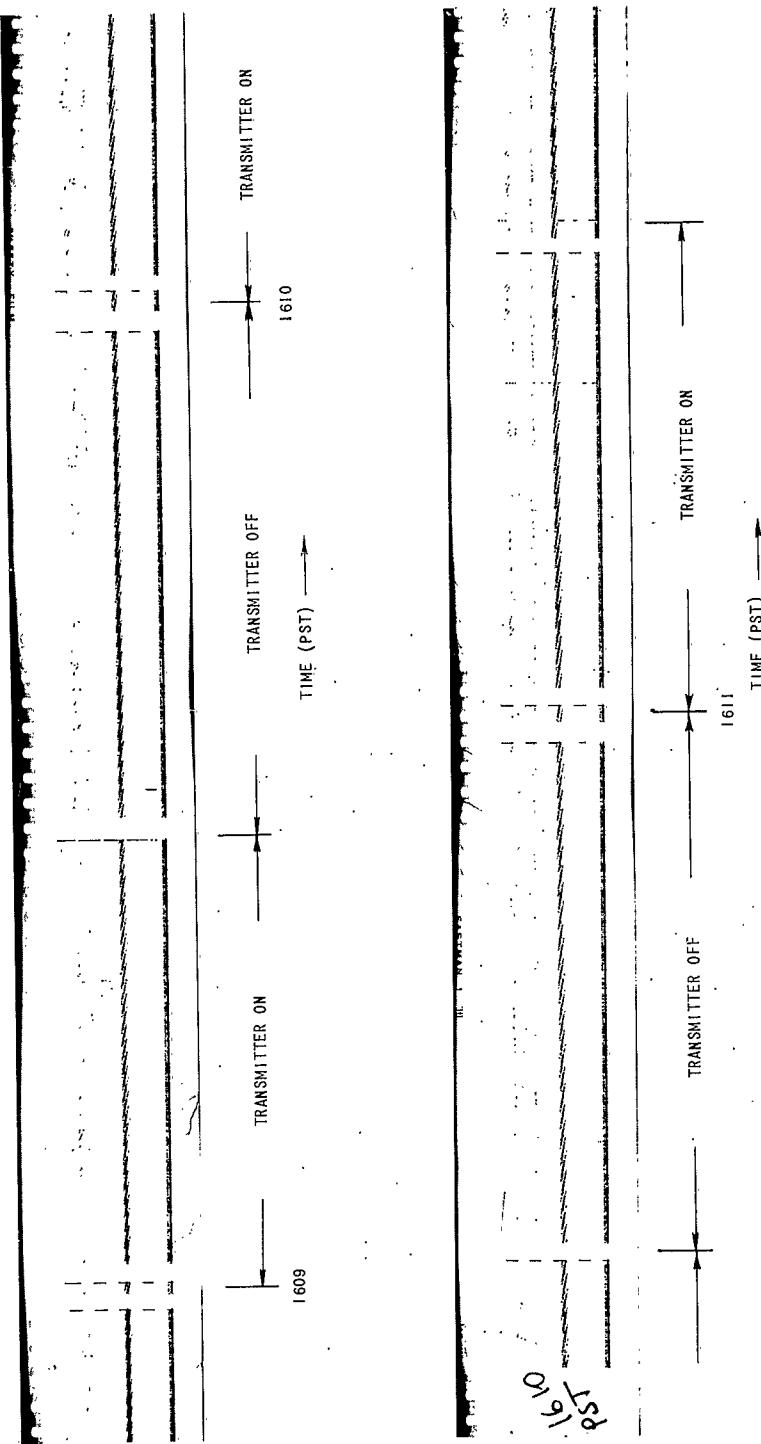


FIG. 4. PHASE-PATH RECORD FOR 16 NOVEMBER 1962.

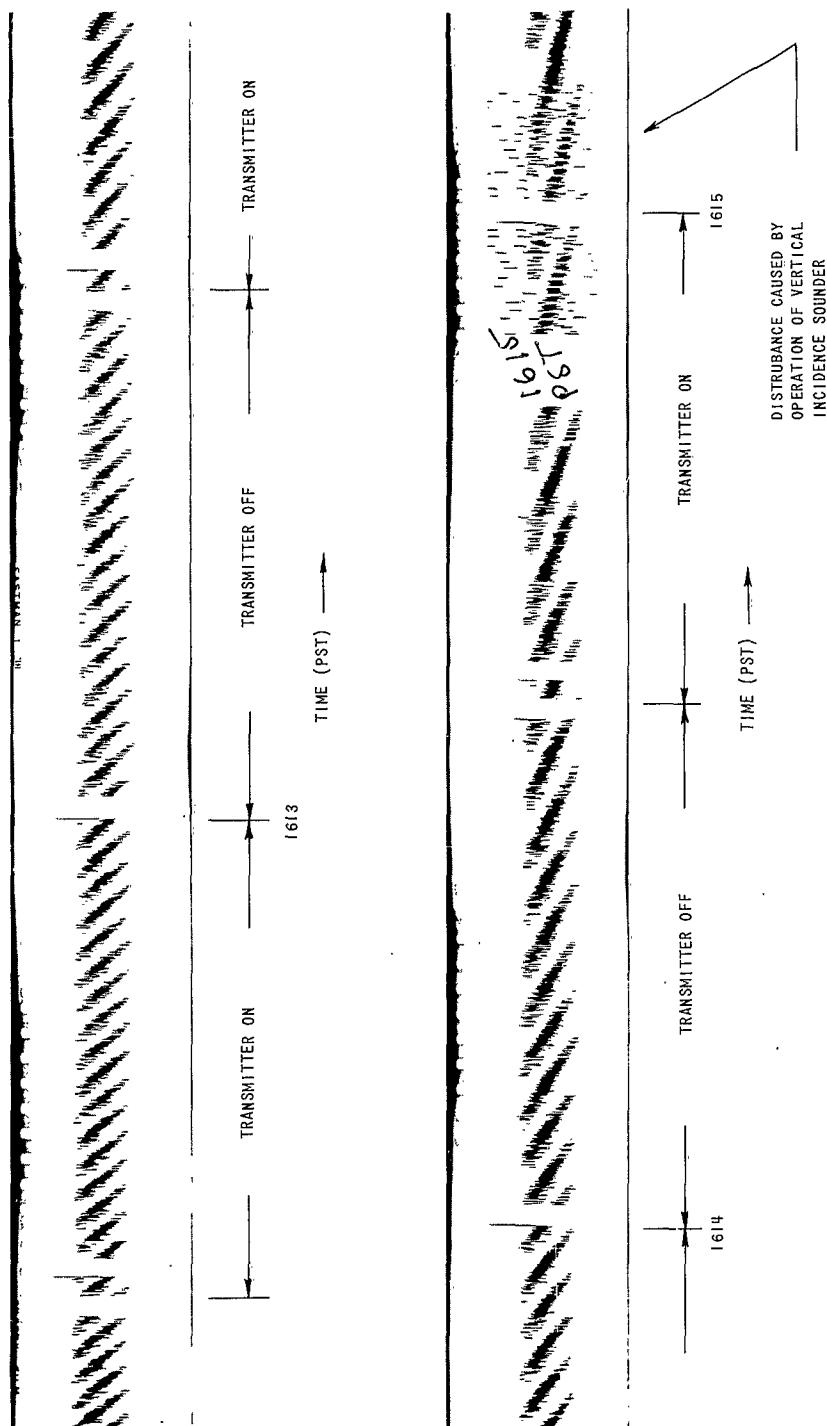


FIG. 5. PHASE-PATH RECORD FOR 16. NOVEMBER 1962 (GAIN INCREASED TO INCLUDE REFLECTED SIGNAL ONLY).

V. COMPARISON WITH THEORY

To calculate steady-state conditions, Farley evaluated the following equations:

1. Within the area of the ionosphere illuminated by the applied field:

$$\begin{array}{l} \text{rate at which} \\ \text{electrons lose} \\ \text{energy to the} \\ \text{heavier} \\ \text{particles} \end{array} + \begin{array}{l} \text{rate at which} \\ \text{electrons lose} \\ \text{energy by} \\ \text{conduction} \end{array} = \begin{array}{l} \text{rate at which} \\ \text{electrons absorb} \\ \text{energy} \end{array} \quad (1)$$

2. outside the illuminated area:

$$\begin{array}{l} \text{rate at which} \\ \text{electrons lose} \\ \text{energy to the} \\ \text{heavier} \\ \text{particles} \end{array} + \begin{array}{l} \text{rate at which} \\ \text{electrons lose} \\ \text{energy by} \\ \text{conduction} \end{array} = 0 \quad (2)$$

The rate at which electrons absorb energy in the ionosphere is given by

$$Q = \frac{1}{2} \sigma E_0^2 = \frac{1}{2} \frac{N e^2 \nu E_0^2}{m_e (\omega^2 + \nu^2)}, \quad (3)$$

where the applied field is $E = E_0 e^{j\omega t}$; N , e , m_e are the density, charge, and mass, respectively, of the electron; ν is the collision frequency, and σ is the electrical conductivity of the plasma. For $\omega \gg \nu$:

$$Q = \frac{1}{2} \frac{N e^2 \nu E_0^2}{m_e \omega^2}. \quad (4)$$

Ginzburg and Gurevich [Ref. 3], give the following expression for the rate at which electrons lose energy to the heavier particles by collisions:

$$L_v(T_e - T_o) = \frac{3}{2} N \delta \nu K(T_e - T_o), \quad (5)$$

where T_e and T_o are the temperatures of the electrons and the heavier particles respectively, K is Boltzmann's constant, and δ is the mean fractional loss of excess energy per collision. The relaxation time for this volumetric loss process is $1/\delta_v$. If the collision frequency is taken to be of the order of 10^3 , and the ions are assumed to be O^+ , this time is of the order of 10 sec.

To simplify the conduction problem, the geometry was reduced to one dimension, since in the F region the gyro frequency is much greater than the collision frequency, so that conduction would be along the lines of magnetic field.

Including conduction effects, Eq. (1) and (2) become

$$L_v(T_e - T_o) - K_{||} \frac{\partial^2}{\partial x^2} (T_e - T_o) = Q \quad |x| \leq x_o \quad (6)$$

$$L_v(T_e - T_o) - K_{||} \frac{\partial^2}{\partial x^2} (T_e - T_o) = 0 \quad |x| > x_o \quad (7)$$

where $K_{||}$ is the coefficient of thermal conductivity in the direction of the magnetic field. Note that all of the "constants" in the differential equation above are temperature dependent. Farley divides the equations above by $K_{||}$ and assumes that $L_v/K_{||}$ is a constant, independent of x , with a value to correspond to the average electron temperature within the beam at a particular height. This assumption insures that $Q/K_{||}$ will be a constant inside the beam. These assumptions are justified by the fact that very small temperature changes are expected. By applying appropriate boundary conditions, the differential equation can be solved. The solution of Eq. (6) is

$$T_e - T_o = \frac{Q}{L_v} (1 - e^{-\alpha x_o} \cosh \alpha x) \quad |x| \leq x_o, \quad (8)$$

where

$$\alpha = \sqrt{L_v/K_{||}}.$$

From Eqs. (4) and (5):

$$\frac{Q}{L_v} = \frac{e^2 E_o^2}{3\omega_m^2 m_e \delta K}$$

so

$$\frac{T_e}{T_o} = 1 + \frac{E_o^2}{E_p^2} \left(\frac{e^2}{3T_o \omega_m^2 m_e \delta K} \right) \left(1 - e^{-\alpha x_o} \cosh \alpha x \right)$$

where

$$\frac{1}{e^2} (3T_o \omega_m^2 m_e \delta K) = E_p^2$$

is the characteristic plasma field introduced by Ginzburg and Gurevich. Therefore:

$$\frac{T_e}{T_o} = 1 + \frac{E_o^2}{E_p^2} \left(1 - e^{-\alpha x_o} \cosh \alpha x \right).$$

The average electron temperature \bar{T}_e inside the beam can be found by integrating over x from $-x_o$ to $+x_o$:

$$\frac{\bar{T}_e}{T_o} = 1 + \frac{E_o^2}{E_p^2} \left[1 - \frac{1}{2\alpha x_o} (1 - e^{-2\alpha x_o}) \right].$$

E_o , in terms of the transmitter parameters, is

$$E_o^2(h) = \sqrt{\frac{\mu_0}{\epsilon_o}} \frac{2\eta P A \rho^2(h)}{\lambda^2 h^2 n} \quad (9)$$

where η is the antenna efficiency, P is the transmitter power, A is the antenna aperature, $\rho^2(h)$ is the attenuation factor due to the losses in the medium, λ is the wavelength of the applied field, h is the height above the antenna, and n is the refractive index. Thus

$$\frac{E_o^2}{E_p^2} = \left(\sqrt{\frac{\mu_o}{\epsilon_o}} \frac{e^2}{6\pi^2 c^2 m_e \delta K T_o} \right) \left(\frac{\eta P A \rho^2(h)}{h^2 n} \right)$$

where

$$\left(\sqrt{\frac{\mu_o}{\epsilon_o}} \frac{e^2}{6\pi^2 c^2 m_e \delta K T_o} \right) = 1.77$$

for $T_o = 1200^{\circ}\text{K}$ and $\delta = 2 m_e/m_i$.

If the refractive index is written as

$$n = \left(1 - \frac{N}{N_c} \right)^{\frac{1}{2}} \quad (10)$$

where N_c is the critical density and

$$C_t = 1.77 \eta A P, \quad (11)$$

we have the equation derived by Farley,

$$\frac{\bar{T}_e}{T_o} = 1 + \frac{C_t \rho^2(h)}{h^2} \left(1 - \frac{N}{N_c} \right)^{-\frac{1}{2}} \left[1 - \frac{1}{2\alpha x_o} \left(1 - e^{-2\alpha x_o} \right) \right]. \quad (12)$$

Farley gives the following for a relation between \bar{T}_e and \bar{N} :

$$\bar{N}(h) = \frac{2}{1 + \bar{T}_e/T_o} N_o(h), \quad (13)$$

where $N_o(h)$ is the initial electron profile (in this case taken as a Chapman layer with a scale height of 50 km and a maximum density of 10^{12} electrons/m³). The attenuation factor $\rho^2(h)$ is the ratio, at h , of the electric field strength to the field strength that would exist in a lossless medium. This factor is a complicated integral expression making Eq. (12) quite difficult to solve. This equation was solved, however, by means of a computer and some results appear in Farley's paper.

A comparison of the parameters of this experiment performed at Stanford with the parameters used by Farley in solving the expression above will give an idea of what magnitude of results to expect. For a 300-meter-diameter, spherical dish antenna with an efficiency of 55 percent, fed by a 50-kw transmitter, and a 50-deg magnetic-dip angle, Farley predicts a 300 °K increase in electron temperature and a 10-percent decrease in electron density. The initial electron-density profile was assumed to be a Chapman layer with maximum density at 300 km. Since the largest changes in the profile will occur at this height, the following calculations were made for $h = 300$ km in Eq. (12). When we rewrite Farley's equation,

$$\frac{\Delta T_e}{T_o} = \frac{C_t \rho^2(h)}{nh^2} f(x_o) \quad (14)$$

where

$$f(x_o) = \left[1 - \frac{1}{2\alpha x_o} \left(1 - e^{-2\alpha x_o} \right) \right].$$

For Farley's calculations,

$$C_t = 3.4(10^9) \text{ m}^2$$

$$f(x_o) = 0.6$$

$$\Delta T_e = 300 \text{ } ^\circ\text{K}$$

In this experiment the power input to the antenna was 40 kw. The total loss in the 600-ohm, open-wire, transmission line between the transmitter and antenna (approximately 530 meters), including the effects of the 3:1 standing-wave ratio, was calculated to be 0.1 db.

Since the beamwidth of the antenna array was actually measured (with the help of an airplane), a simple calculation can be made to determine the effective aperature. For the 12-deg beamwidth at 7700 kc the aperature is $3.45 (10^4) \text{ m}^2$. It may be observed that the actual physical area containing the dipoles (see Fig. 2) is $3.10 (10^4) \text{ m}^2$.

The efficiency of this antenna array is difficult to calculate with any degree of accuracy. The effect of the single reflector is questionable. Thus, for the following calculations, the efficiency will be assumed to be 50 percent.

Therefore, for this experiment, the factor C_t equals $1.2 (10^9) m^2$ in Eq. (14). For a 300-km height, a magnetic-dip angle of 60 deg, and a 12-deg beamwidth, $f(x_0)$ in Eq. (14) is equal to 1.0. At a given height $\rho^2(h)$, n , and h^2 will be constants in Eq. (14), so that the following ratio may be taken:

$$\frac{(\Delta T_e)_\text{Stanford}}{(\Delta T_e)_\text{Farley}} = \frac{(\Delta T_e)_s}{300} = \left(\frac{1.2}{3.4} \right) \left(\frac{1.0}{0.6} \right) = 0.59$$

therefore,

$$(\Delta T_e)_s = 177 \text{ } ^\circ\text{K}$$

$$N(h) = \left(\frac{2}{2 + 177/1200} \right) N_0(h)$$

$$N(h) = 0.93 N_0(h)$$

Hence, with the equipment used in the Stanford heating experiment, a 7-percent decrease in electron density or a $3\frac{1}{2}$ -percent decrease (270 kc) in the critical frequency should have been observed.

If a 3-db power loss is assumed (because of round-trip D-region absorption or inefficient power radiation) the increase in electron temperature would be only $88 \text{ } ^\circ\text{K}$ and the corresponding decrease in electron density would be $3\frac{1}{2}$ percent (or about a 1.75-percent decrease in the critical frequency--135 kc).

VI. SUMMARY

A radio beam with a frequency slightly below the critical frequency was directed toward the F region of the ionosphere in an effort to cause a modification of the electron density profile. A comparison with calculations made by D. T. Farley indicates that, with the equipment used for this experiment, a $3\frac{1}{2}$ -percent decrease in the maximum of the electron-density profile (assuming the electron-density profile to be given by a Chapman layer with a scale height of 50 km and a maximum density of 10^{12} electrons/m³ at a height of 300 km) should have been observed. This change corresponds to a reduction of 135 kc in the critical frequency from 7700 kc.

A phase-path sounder used to measure changes in the phase-path height, and a vertical-incidence sounder used to measure the virtual height, (both estimated to be sensitive to a 50-kc change in the critical frequency) were unable to detect any changes in several trials of the experiment. Since it was impossible to hold the heating frequency equal to slightly below the critical frequency, and the expected changes were marginal, the actual changes may have been too small to have been detected by the measuring equipment. It is also probable that not all factors contributing to the attenuation of the heating signal were taken into account.

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